

# Multi-frequency linear and circular radio polarization monitoring of jet emission elements in *Fermi* blazars

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**Abstract:** Radio emission in blazars – the aligned subset of Active Galactic Nuclei (AGN) – is produced by synchrotron electrons moving relativistically in their jet’s magnetic field. Under the assumption of some degree of uniformity of the field, the emission can be highly polarized – linearly and circularly. In the radio regime, the observed variability is in most of the cases attributed to flaring events undergoing opacity evolution, i.e. transitions from optically thick to thin emission (or vice versa). These transitions have a specific signature in the polarization parameter space (angle and magnitude) which can be traced with high cadence polarization monitoring and provide us with a unique probe of the microphysics of the emitting region. Here we present the full Stokes analysis of radio emission from blazars observed in the framework of the F-GAMMA program and discuss the case study of PKS 1510–089 which has shown a prominent polarization event around MJD 55900.

## 1 Introduction

Blazars – including Flat Spectrum Radio Quasars (FSRQs) and BL Lac objects – comprise the most extreme manifestation of the AGN phenomenon. The combination of relativistic speeds and small angles of their jet to our line of sight (a few degrees [1]), results in an extreme phenomenology. Their emission is beamed and boosted showing intense variability at all time scales (from years down to hours), very high brightness temperatures, highly superluminal apparent speeds and others. They emit a remarkably broadband spectral energy distribution (SED) spanning from radio to TeV energies, with variability seen throughout its entirety. The broadness of their SED is caused by incoherent synchrotron processes involving most likely electrons which – at second order – are Inverse-Compton upscattering photons to very high energies. The synchrotron part is intrinsically polarized to a degree that depends on opacity [6].

The radio tail of the synchrotron component is practically entirely attributed to the large scale jet. The variability seen in these frequencies in most of the cases shows signature of spectral evolution and transition from optically thick to thin regime. This alone makes the radio emission, and especially its polarized part, an excellent probe of the microphysics of extragalactic jets. In the following, and after a brief review of the mechanisms believed to be responsible for polarization, we show a case study to demonstrate the insight that such studies can provide and discuss the techniques and methods that are involved in this endeavor.

## 2 Polarized emission from relativistic jets

The AGN radio emission is attributed to incoherent synchrotron radiation of relativistic electrons and therefore, it is expected to be polarized. Under certain conditions, a rather high degree of linear or circular polarization could be observed. The condition for significant polarization is the degree of uniformity of the magnetic field implying that polarization probes uniformly magnetized regions of the plasma and trace their behavior in time. Multi-band linear and circular radio polarization monitoring is then an invaluable tool for the investigation of the physical properties of AGN jets such as the topology

and magnitude of their magnetic fields [2], their composition [3, 4] and structural characteristics of their environment [5].

The degree of linear polarization in the optically thin case and under the assumption of uniform magnetic field, is expected to be as high as almost 72 % ( $m_l^{(\text{thin})} = (|\alpha| + 1)/(|\alpha| + \frac{5}{3})$  with  $\alpha$  the spectral index defined as  $S_\nu \propto \nu^\alpha$  [6]). The electric vector (EV) is perpendicular to the projection of the magnetic field onto the plane of the sky. The emission is expected to be also circularly polarized with its handedness to depend on the viewing angle of the system. The expected circular polarization degree is generally a tiny fraction of the linear polarization and has a frequency dependence of the form:  $m_c^{(\text{thin})} \propto \nu^{-\frac{1}{2}}$ .

At low radio frequencies – where the synchrotron emission is self-absorbed – the degree of linear polarization drops to  $m_l^{(\text{thick})} = 3/(12|\alpha| + 19) \approx 11\%$  with the EV parallel to the projection of the magnetic field onto the plane of the sky, and the circular polarization degree follows the same spectral dependence though with the opposite handedness [6]. In the radio regime the spectrum is expected to undergo the transition between optically thin and thick emission [7]. This makes multi-frequency polarization observations a unique diagnostic tool for the detailed study of the radiative mechanism.

High-cadence polarization monitoring, can trace the dynamics of the associated physical characteristics [8]. Polarization variability takes place mainly in two domains: (a) the polarization amplitude and (b) the electric vector position angle (EVPA). EVPA variability has been observed in the past in the form of polarization angle swings (e.g. [9, 10, 11]). Such swings can be attributed to either of two mechanisms: (a) **Geometrical swing**: The swing is caused by the motion of a synchrotron emitting cloud of electrons in a helical path and the rotation can have theoretically an arbitrary magnitude depending on the helical path and the line of sight. (b) **Radiative “swing”**: The rotation is caused by the transition from the optically thick to thin regime (or vice versa) of the synchrotron self-absorbed spectrum. As a jet emission element expands, its density and consequently its optical thickness,  $\tau$ , decrease. When  $\tau \approx 1$ , the linear as well as the circular polarization degrees drop to zero before gaining the values associated with the optically thin (or thick) regime mentioned earlier, while the EVPA changes by exactly  $90^\circ$ .

The described mechanisms can also operate simultaneously. However, it is essential that only in the radio regime where dynamic outbursting activity induces opacity evolution – can radiative swings be studied.

### 3 The F-GAMMA program and radio polarization data analysis

Despite the unique potential of the polarimetric studies and especially of polarization monitoring investigations, the observational challenges involved are often insurmountable. The F-GAMMA program is a radio multi-frequency *Fermi* blazar monitoring program operating since January 2007 [12, 13], providing a database suitable for such studies. Observations are conducted with 3 main facilities: the 100-m Effelsberg, the 30-m IRAM and the 12-m APEX telescopes. The datasets consist of light curves at 11 radio frequencies from 2.64 to 345 GHz, linear polarization for 5 frequencies between 2.64 and 14.6 GHz and circular polarization for 7 frequencies between 2.64 to 43 GHz for  $\sim 60$   $\gamma$ -ray blazars with a mean cadence of 1.1 months.

The difficulty of polarization measurements of AGN is apparent due to the low degree of polarization in the radio band. As an example, at 5 GHz, 75 % of the F-GAMMA sources are linearly polarized with median linear polarization degree ( $\tilde{m}_l$ ) of 3.1 % and 2 % are circularly polarized with median circular polarization degree ( $\tilde{m}_c$ ) of 0.4 %. At 10 GHz, 39 % of the sample is linearly polarized with  $\tilde{m}_l = 3.6\%$  and 5 % is circularly polarized with  $\tilde{m}_c = 0.4\%$ <sup>1</sup>.

The state of polarization can be described by the Stokes vector,  $\mathbf{S} = (I, Q, U, V)$ , where  $I$  is the total intensity,  $Q$  and  $U$  describe the linear and  $V$  the circular polarization characteristics. Instrumental effects which alter the polarization state of the incident radiation, can be described by the Müller matrix,  $\mathbf{M}$ , a transfer function between the real and the observed Stokes parameters:  $\mathbf{S}_{\text{obs}} = \mathbf{M} \cdot \mathbf{S}_{\text{real}}$ .

The applied analysis to correct for instrumental effects can be broken down to: (a) observe sources of known polarization parameters (standards), (b) with knowns the observed and the expected Stokes

<sup>1</sup>These values refer to  $3\sigma$  detections of the linear and circular polarization flux.

vectors, compute the elements of the Müller matrix. For an over-determined system, a least-squares fit method is applied and (c) apply the inverse of the computed Müller matrix to the observed Stokes vector for the target sources [14].

The reduction scheme described above is usually applied only for linear polarization measurements owing to the lack of circular polarization standards. The advantage however in our case is the fact that the receivers are equipped with circularly polarized feeds which allow satisfactory measurements after precise gain correction using observations of unpolarized sources. A number of sources with significant circular polarization flux have been detected as well as sources with stable circular polarization parameters which could be used as standards, such as 3C295 and 3C48 which have circular polarization degrees of  $0.6 \pm 0.1\%$  and  $0.6 \pm 0.2\%$  at 5 GHz respectively.

## 4 PKS 1510–089: a case study

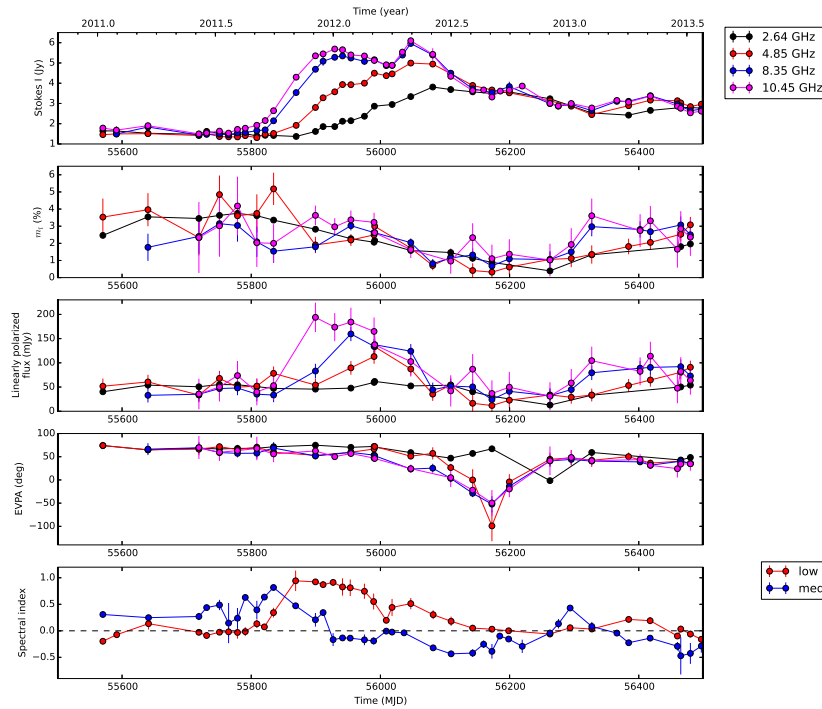


Figure 1: Polarization parameters of the blazar PKS 1510–089, as obtained with the F-GAMMA program. From top to bottom: Stokes  $I$ , linear polarization degree  $m_l$ , linearly polarized flux, EVPA and spectral index in two radio bands ( $\alpha_{2.6}^{8.4}$  and  $\alpha_{10.5}^{23.1}$ ).

PKS 1510–089 is among the best studied blazars (FSRQ). It has shown geometrically induced rotations of the EVPA [15]. As an example case study, we discuss the radio polarimetric data that display a very interesting behavior. In Fig. 1, from top to bottom, is shown: Stokes  $I$ , the degree of linear polarization  $m_l$ , the linearly polarized flux, the EVPA and the spectral index in two radio bands: low ( $\alpha_{2.6}^{8.4}$ ) and intermediate ( $\alpha_{10.5}^{23.1}$ ).

What is immediately visible in the Stokes  $I$  panel is that the source underwent a major flaring event from MJD 55800 to MJD 56200, less discernible towards lower frequencies. The highest peak appears around MJD 56050 and with a phase difference between the 4 frequencies, due to opacity effects. The spectrum shows profound evolution during the flare. In the low band, it starts off as flat ( $\alpha \approx 0$ ) and hardens (becoming optically thicker) during the outburst before flattening again. A major  $\gamma$ -ray event preceded the radio one for about 140 days at MJD  $\approx 55860$  [16].

The polarization follows this evolution closely. During the flaring event, the polarization degree remains fairly stable ( $\approx 2 - 3\%$ ) and the polarized flux shares the characteristics of Stokes  $I$ . The stability of the polarization degree over the flaring event implies that no opacity transition takes place

as it can also be seen in the spectral index behavior which remains optically thick ( $\alpha > 0$ ). The EVPA shows a very interesting behavior. At the beginning of 2011 (MJD  $\approx 55600$ ) it is  $\sim 65^\circ$ , roughly perpendicular to the jet axis [15]. Around MJD 56170 it shows two prominent rotations. During the former rotation (up to MJD 56170), the EVPA rotates for  $\approx 125^\circ$  ( $65^\circ$  to  $-60^\circ$ ) in total with a pace of  $1.2^\circ$  per day at 5 GHz and  $0.5^\circ$  per day at 10 GHz. During the latter one (from MJD 56170 on) it rotates in the opposite sense until it reaches  $\approx 40^\circ$  ( $-60^\circ$  to  $40^\circ$ ) with a pace of  $1.2^\circ$  per day at 5 GHz and  $0.8^\circ$  per day at 10 GHz.

In order to explain the observed behavior, we assume that an optically thick emission element which is responsible for the major Stokes  $I$  event undergoes a slow geometrically induced rotation (Sec. 2), from  $65^\circ$  to  $40^\circ$ , first at 10 GHz (up to MJD  $\approx 56000$ ) and then at 5 GHz (up to MJD  $\approx 56100$ ), because the polarization degree remains stable and the spectral index remains thick all the time. Then the same emission element becomes optically thin and EVPA rotates by  $90^\circ$  becoming roughly parallel to the jet axis [15] (fast rotation before MJD 56170,  $40^\circ$  to  $-50^\circ$  at 10 GHz) during a concurrent minimization of the polarization degree and flux, a characteristic of radiative swings as described in Sec. 2. Finally, a subsequent optically thick emission element, possibly the one responsible for the short flare around MJD 56420, rotates the EVPA again by  $90^\circ$ , perpendicular to the jet axis [15] (fast rotation after MJD 56170,  $-50^\circ$  to  $40^\circ$  at 10 GHz). Both fast rotations around MJD 56170 are then of the radiative kind (Sec. 2) as it is also suggested by the fact that their paces are very similar.

Assuming that the radiative swing does not occur simultaneously with the optical depth transition, as it is derived in [6], an alternative interpretation would be that the first emission element has already the optically thin polarization characteristics at the beginning of our measurements. This could explain the high polarization degree. Then the second emission element would be responsible for both radiative EVPA swings around MJD 56170. The second element which is initially optically thick, rotates the EVPA to  $-50^\circ$  ( $90^\circ$  rotation) and reduces the polarization degree. Later it becomes optically thin, rotating the EVPA back to  $40^\circ$  and increasing the polarization degree once more.

## 5 Summary

The prominent variability and the associated spectral evolution of blazars carry a characteristic signature in their polarized radio emission, providing a unique probe of the microphysics of the emitting region. After an introduction for the study of blazar physics using multi-band high-cadence polarization monitoring, we described the full Stokes analysis of the F-GAMMA database. Finally, we focused on the case study of PKS 1510–089 which showed an interesting polarization event around MJD 55900.

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